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Nonlinear Seismic Response Analysis of Concrete Gravity Dams Considering Soil-Structure Interaction

Mokhtar Messaad*[1], Djamel Ouzandja[2], Taieb Messaad[3]

[1]*Department of Civil Engineering, University of Biskra, Biskra, Algeria*

[2]*Department of Civil Engineering, University of Msila, Msila, Algeria*

[3]*Department of Civil Engineering, University of Tiaret, Tiaret, Algeria*

[1] mokhtar.messaad@univ-biskra.dz

[2] taieb.messaad@univ-tiaret.dz

[3] djamel.ouzandja@univ-msila.dz

Abstract: The stability analysis of the dams subjected to seismic loads is really very complex. One of the most important problems in evaluation of seismic behavior of concrete gravity dams is soil-structure interaction phenomenon. In this paper, we study the effect of soil-structure interaction (SSI) on seismic response of concrete gravity dams. For this purpose, two finite element models using ANSYS software are generated. The first model represents the dam alone, which is fixed at its bottom base (model without SSI). The second model illustrates the dam-foundation rock coupled system (model with SSI). Oued Fodda concrete gravity dam, located in the north-west of Algeria, is chosen in the present study. The Drucker-Prager model is considered in the nonlinear analysis for concrete of dam body. Reservoir water is modeled using Westergaard approach. According to finite element analysis, numerical results show that taking into account of soil-structure interaction phenomenon increase more displacements and stresses in the dam body. Therefore, it is becomes imperative to carry out the soil-structure interaction analysis for massive structures such as concrete dams in order to evaluate their stability.

Keywords: Concrete Gravity dam, dynamic soil-structure interaction, finite element method, nonlinear seismic response.

1. INTRODUCTION:

There are various factors affecting the stability of concrete dams during seismic motions. One of them is the soil-structure interaction. The seismic response of a dam depends upon characteristics of the seismic motion, the foundation soil and the dam itself. Several researchers investigated the seismic response of concrete gravity dams including soil-structure interaction phenomenon [1-7].

Chopra and Chakrabarti [8] presented the earthquake analysis of concrete gravity dams including fluid-structure-soil interaction. Nuss et al. [9] studied the effect of soil-structure interaction on seismic stability of concrete dams. The influence of foundation rock properties on the deynamic behavior of dam-reservoir-foundation interaction systems was investigated by bayraktar et al. [10]. Burman et al. [11] proposed a simple iterative method for the dynamic analysis of concrete dam-foundation interaction problems. Saleh and Madabhushi [12] illustrated the seismic response of concrete dams on rigid and soil foundation. A transient analysis of a gravity dam using a simplified direct method considering the effect of soil-structure interaction was carried out by Burmanet al. [13]. Mirzabozorg et al. [14] investugated the seismic response of dam-reservoir-foundation system in time domain using finite element method. Ouzandja et al. presented the response of concrete gravity dams considering foundation flexibility under seismic loading [15]. The effect of foundation rock roughness on seismic performance of concrete gravity dams was studied by Ouzandja and Tiliouine [16].

This work presents the nonlinear seismic response transient analysis of concrete gravity dams considering soil-structure interaction. Oued fodda concrete gravity dam, located in the north-west of Algeria, is selected as an example in this study. For this purpose, two finite element models using ANSYS software [17] are taken into account. The first model represents the dam alone, which is fixed at its bottom base (model without SSI). The second model illustrates the dam-foundation rock coupled system (model with SSI). The effect of hydrodynamic pressure is modeled using the added mass approach [18]. The Drucker-Prager model [19] is employed in the nonlinear analysis for concrete of dam body.

2. MATHEMATICAL FORMULATION OF SOIL-STRUCTURE COUPLED SYSTEM

In soil-structure interaction problems, the foundation soil and the structure do not vibrate as separate systems under external excitations, rather they act together in a coupled way. Therefore, these problems have to be dealt in a coupled way. The most common soil-structure interaction (SSI) approach used is based on the "added motion" formulation. In order to develop the fundamental SSI dynamic equilibrium equations, we consider the soil-structure system shown in Fig. 1.

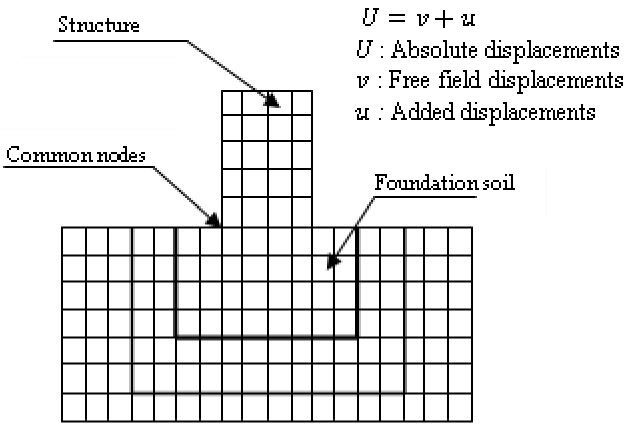


Fig.1 Soil-structure interaction system

The SSI model here is divided into three sets of node points [19]. The common nodes at the interface of the structure and soil are identified with the subscript "c"; the nodes within the structure are with "s" and the nodes within the foundation soil are with "f ". In this figure, the absolute displacement (U) is estimated out of the sum of the free field displacement (v) and the added displacement (u).

From the direct stiffness approach in structural analysis, the dynamic force equilibrium of the system is given in terms of the absolute displacements U, by the following sub-matrix equation:

$$\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sc} & 0 \\ C_{cs} & C_{cc} & C_{cf} \\ 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{U}_s \\ \dot{U}_c \\ \dot{U}_f \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} U_s \\ U_c \\ U_f \end{Bmatrix} = - \begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{U}_s^g \\ \ddot{U}_c^g \\ \ddot{U}_f^g \end{Bmatrix} \quad (1)$$

where the mass and stiffness at the contact nodes are the sum of the contributions from the structure (s) and foundation soil (f), and are given by:

$$M_{cc} = M_{cc}^{(s)} + M_{cc}^{(f)}, C_{cc} = C_{cc}^{(s)} + C_{cc}^{(f)}, K_{cc} = K_{cc}^{(s)} + K_{cc}^{(f)} \tag{2}$$

In order to solve the coupled soil-structure interaction problem, we would require to solve Eq. (1). Having solved Eq. (1) using Newmark's integration method, one would obtain the absolute displacements, velocities and accelerations of the coupled SSI problem. To avoid solving the SSI problem directly, the dynamic response of the foundation without the structure is calculated. The free-field solution is designated by the free-field displacements v, velocities $\dot{v}$ and accelerations $\ddot{v}$. Here, $\ddot{U}^g$ is the ground acceleration vector. By a simple change of variables, it becomes possible to express the absolute displacements U, velocities $\dot{\boldsymbol{U}}$ and accelerations $\ddot{\boldsymbol{U}}$ in terms of displacements u, relative to the free-field displacements v. Or,

$$\begin{Bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{Bmatrix} = \begin{Bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{Bmatrix} + \begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{Bmatrix} \quad \begin{Bmatrix} \dot{U}_s \\ \dot{U}_c \\ \dot{U}_f \end{Bmatrix} = \begin{Bmatrix} \dot{v}_s \\ \dot{v}_c \\ \dot{v}_f \end{Bmatrix} + \begin{Bmatrix} \dot{u}_s \\ \dot{u}_c \\ \dot{u}_f \end{Bmatrix} \quad \begin{Bmatrix} U_s \\ U_c \\ U_f \end{Bmatrix} = \begin{Bmatrix} v_s \\ v_c \\ v_f \end{Bmatrix} + \begin{Bmatrix} u_s \\ u_c \\ u_f \end{Bmatrix} \tag{3}$$

After replacing the values of $\ddot{U}$, $\dot{U}$ and U from Eq. (3), Eq. (1) is expressed as

$$\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{Bmatrix} \begin{bmatrix} C_{ss} & C_{sc} & 0 \\ C_{cs} & C_{cc} & C_{cf} \\ 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{u}_s \\ \dot{u}_c \\ \dot{u}_f \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} u_s \\ u_c \\ u_f \end{Bmatrix} = R + F \tag{4}$$

Where

$$R = -\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{v}_s \\ \ddot{v}_c \\ \ddot{v}_f \end{Bmatrix} - \begin{bmatrix} C_{ss} & C_{sc} & 0 \\ C_{cs} & C_{cc} & C_{cf} \\ 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{v}_s \\ \dot{v}_c \\ \dot{v}_f \end{Bmatrix} - \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} v_s \\ v_c \\ v_f \end{Bmatrix} \tag{5}$$

$$\text{and, } F = -\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{U}_s^g \\ \ddot{U}_c^g \\ \ddot{U}_f^g \end{Bmatrix} \tag{6}$$

This is a numerically cumbersome approach; hence, an alternative approach is necessary to formulate the solution directly in terms of the absolute displacements of the structure. Since the analysis is now for the foundation part only (free field analysis), hence the corresponding values of the displacement, velocity and acceleration for the structural part is taken as zero. This involves the introduction of the following change of variables:

$$\begin{Bmatrix} \ddot{U}_s \\ \ddot{U}_c \\ \ddot{U}_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ \ddot{v}_c \\ \ddot{v}_f \end{Bmatrix} + \begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{Bmatrix} \quad \begin{Bmatrix} \dot{U}_s \\ \dot{U}_c \\ \dot{U}_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ \dot{v}_c \\ \dot{v}_f \end{Bmatrix} + \begin{Bmatrix} \dot{u}_s \\ \dot{u}_c \\ \dot{u}_f \end{Bmatrix} \quad \begin{Bmatrix} U_s \\ U_c \\ U_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ v_c \\ v_f \end{Bmatrix} + \begin{Bmatrix} u_s \\ u_c \\ u_f \end{Bmatrix} \tag{7}$$

In order to calculate the free field displacement sv, only foundation domain is solved by considering no structure is present on it. The foundation domain is subjected to earthquake motion and the free-field displacement for the common and other foundation nodes are obtained.

$$\begin{bmatrix} M_{cc} & M_{cf} \\ M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{v}_c \\ \ddot{v}_f \end{Bmatrix} + \begin{bmatrix} C_{cc} & C_{cf} \\ C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{v}_c \\ \dot{v}_f \end{Bmatrix} + \begin{bmatrix} K_{cc} & K_{cf} \\ K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} v_c \\ v_f \end{Bmatrix} = -\begin{bmatrix} M_{cc} & M_{cf} \\ M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{U}_c^g \\ \ddot{U}_f^g \end{Bmatrix} \tag{8}$$

After obtaining the free field response (i.e. v,v˙ and v¨) the interaction force R is calculated using Eq. (9) in the following simplified manner:

$$R = -\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ \ddot{v}_c \\ 0 \end{Bmatrix} - \begin{bmatrix} C_{ss} & C_{sc} & 0 \\ C_{cs} & C_{cc} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ \dot{v}_c \\ 0 \end{Bmatrix} - \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ v_c \\ 0 \end{Bmatrix} \tag{9}$$

After obtaining the interaction forces R, the added responses of the structure and foundation soil domain are calculated using Eq. (10). And then the added responses (i.e. u, ,u˙ and u¨) are added to the free field responses to get the absolute responses of the coupled soil and structure domain, following Eq. (7):

$$\begin{bmatrix} M_{ss} & M_{sc} & 0 \\ M_{cs} & M_{cc} & M_{cf} \\ 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{u}_s \\ \ddot{u}_c \\ \ddot{u}_f \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sc} & 0 \\ C_{cs} & C_{cc} & C_{cf} \\ 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{u}_s \\ \dot{u}_c \\ \dot{u}_f \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sc} & 0 \\ K_{cs} & K_{cc} & K_{cf} \\ 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} u_s \\ u_c \\ u_f \end{Bmatrix} = R + F \tag{10}$$

The main assumptions used in this model are that the input motions at the level of the base rock are not considered to be affected by the presence of the structure and that all interface nodes will be subjected to the same free-field accelerogram [1]. In theory any desired spatial variation of the free-field components could be considered at the interface, but there is seldom sufficient information to specify such variation. In this case, the mass of the foundation is taken into account in the analysis such that it will represent the soil-structure interaction in a relatively more realistic manner.

3. FINITE ELEMENT MODELS OF DAM-FOUNDATION ROCK SYSTEM

The Oued Fodda concrete gravity dam is located in the north-west of Algeria. The geometry of the Oued Fodda dam is illustrated in the Fig. 2. The dam-foundation rock system is investigated using two numerical models. The first model represents the dam alone, which is fixed at its bottom base, i.e., dam without SSI (Fig. 3). The second model represents the dam-foundation coupled system, i.e., dam with SSI (Fig. 4). The hydrodynamic pressure the reservoir fluid is considered according to Westergaard technic [18]. The different finite element models are generated using ANSYS software [17].

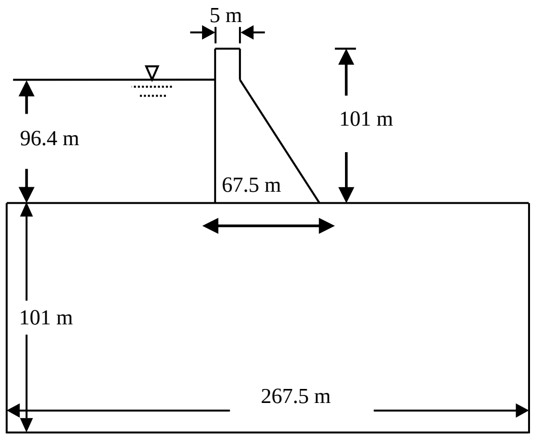


Fig.2 Dam-foundation rock system

A two-dimensional (2D) finite element model with 937 nodes and 288 plane solid elements (PLANE 82) is used to model dam body alone (Fig. 3). A two-dimensional (2D) finite element model with 4795 nodes and 792 plane solid elements (PLANE 82) is used to model dam-foundation coupled system (Fig. 4). A finite element model with 20 structural masses (Mass21) is used to model the reservoir fluid.

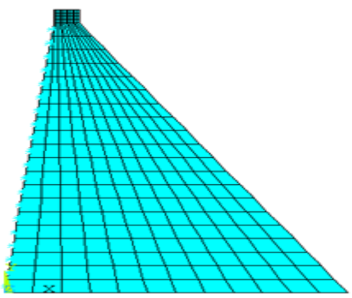


Fig.3 Finite element model of dam body alone

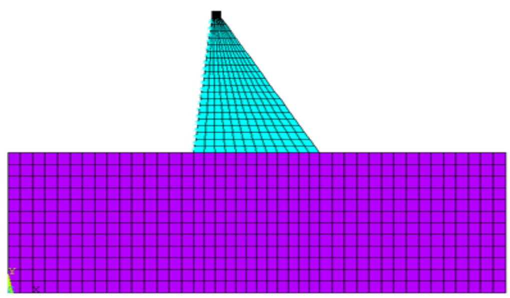


Fig.4 Finite element model of dam-foundation rock system

The material properties of Oued Fodda dam and its foundation are reported in Table 1 below. According to the Drucker-Prager model [19], the cohesion and the angle of internal friction of the dam body are assumed as to be 2.50 Mpa and 35°. The tensile strength and the compressive strength of the concrete of the dam are 1.6 MPa and 20 MPa, respectively [20].

Table1: Material properties of the dam and its foundation rock

Material	Material properties		
	Modulus of elasticity (MPa)	**Poisson's ratio**	**Mass density (kg/m3)**
Concrete dam	24600	0.20	2640
Foundation	20000	0.33	2000

4. SEISMIC ANALYSIS AND RESULTS

A. *Modal analysis*

Table 2 below shows the first five natural frequencies for models without and with SSI. It is observed that frequencies are very important in model without SSI, which implies that the fixed dam at its base is rigid.

Table2: Material properties of the dam and its foundation rock

Mode	Frequency (Hz)	
	Dam alone	**Dam-foundation coupled system**
1	3.286	2.561
2	7.882	5.610
3	10.027	6.106
4	13.670	8.134
5	20.273	10.567

B. *Nonlinear seismic response of Oued Fodda Dam*

This study investigates the nonlinear seismic response of Oued Fodda concrete gravity dam considering soil-structure interaction phenomenon. The horizontal component of 2003 boumerdes earthquake during 20 s with peak ground acceleration (pga) 0.34 g is employed in analyses (Fig. 5). Time history analysis is performed using ANSYS software [17]. Newmark algorithm is utilized in numerical solutions. The Drucker-Prager model [19] is used in the nonlinear analysis for concrete of the dam body. According to the numerical analyses, the maximum horizontal displacements in upstream direction and the maximum horizontal, vertical and shear stresses in the dam along its height are presented for both models without and with SSI.

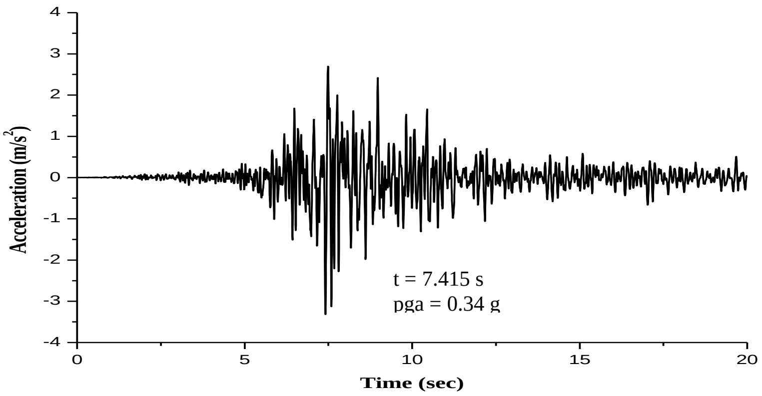


Fig.5 Acceleration records of 2003 Boumerdes earthquake

C. *Horizontal Displacements*

The Fig. 6 represents the maximum horizontal displacements of dam in upstream direction obtained from transient analyses for models without and with SSI. According to numerical analyses, the soil-structure interaction increases the horizontal displacements along the dam height. As seen in Fig. 6, the maximum displacements occur at the dam crest in model with SSI.

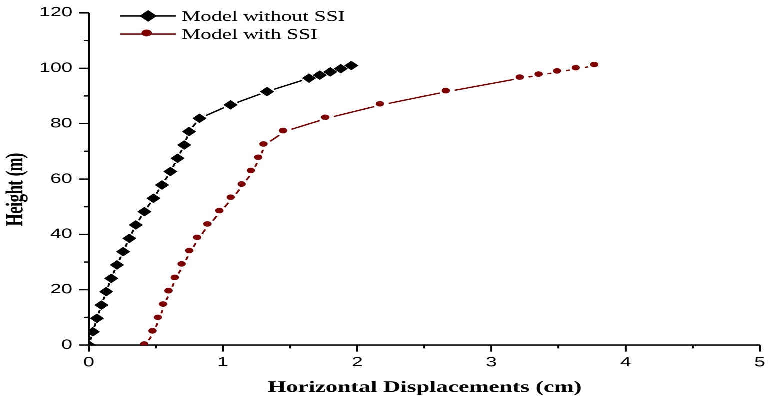


Fig.6 Maximum horizontal displacements in upstream direction for model without SSI and model with SSI

The time history of horizontal displacement at the crest of dam is presented in Fig. 7 for both models without and with SSI. The horizontal displacement at crest increases from 1.96 cm in model without SSI to 3.78 cm in model with SSI. This indicates that there is about 93 % rise in the magnitude of the crest displacement in model with ISS. It is obvious that the horizontal displacements obtained from model with SSI are higher than ones obtained from model without SSI due to the effect of soil-structure interaction phenomenon. The Fig. 8 shows the maximum horizontal displacement contours at the crest of dam for model without SSI and model with SSI.

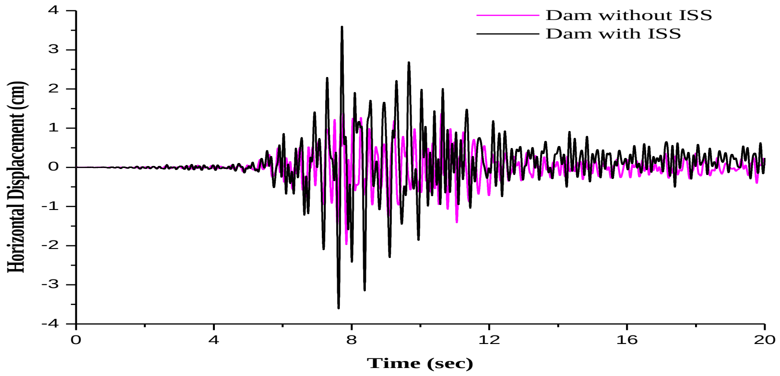
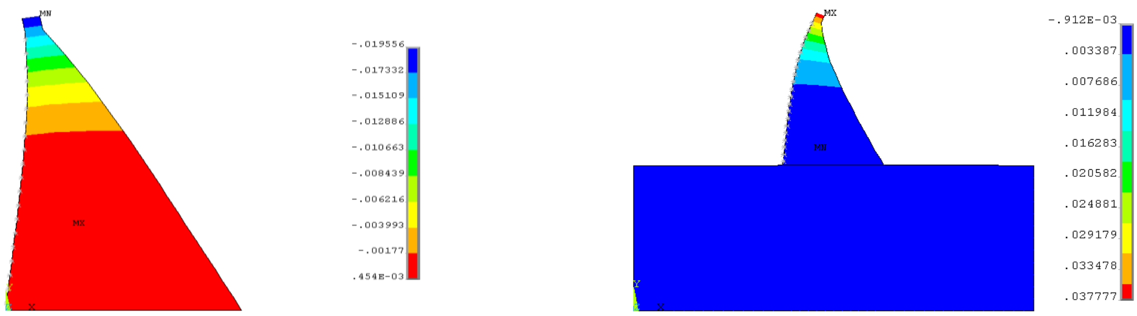


Fig.7 Time history of horizontal displacement at crest of dam for model without SSI and model with SSI



a) Model without SSI b) Model with SSI

Fig. 8 Maximum horizontal displacement contours of the dam

D. *Stresses*

The Figs. 9, 10 and 11 show the maximum horizontal and vertical as well as shear stress distributions along the dam height for both models without and with SSI. Numerical analyses indicate that soil-structure interaction increases the maximum stresses into the dam along its height. It is observed that the maximum horizontal, vertical and shear stresses increase from 0.39 Mpa, 3.33 Mpa and 0.38 Mpa, respectively, in model without SSI to 0.67 Mpa, 5.60 Mpa and 0.65 Mpa in model with SSI. Therefore, for model with SS, an increase of 72 %, 68 % and 71 %, respectively, in the magnitude of horizontal and vertical as well as shear stress values is noticed.

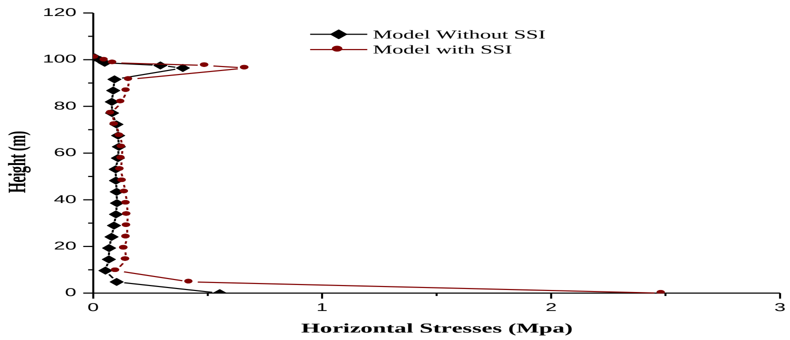


Fig. 9 Distribution of horizontal stresses along dam height for model without SSI and model with SSI

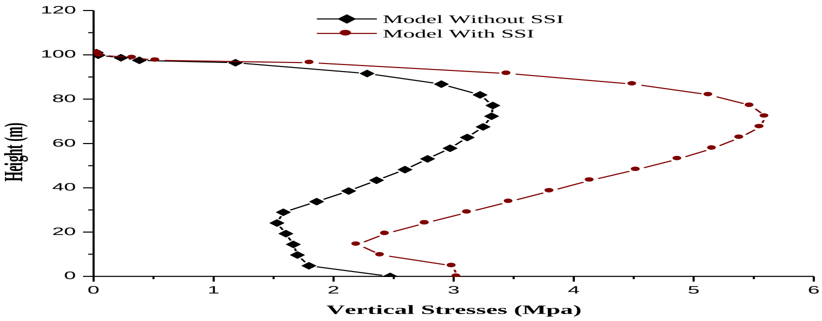


Fig.10 Distribution of vertical stresses along dam height for model without SSI and model with SSI

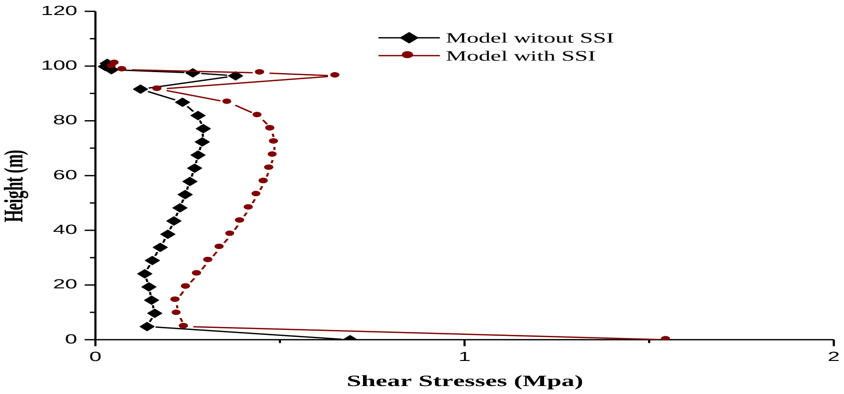


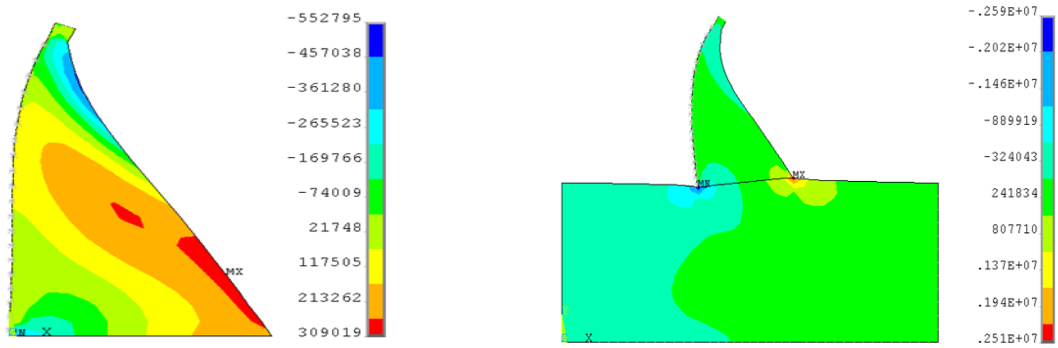
Fig.11 Distribution of shear stresses along dam height for model without SSI and model with SSI

Table 3 below shows the maximum horizontal, vertical and shear stress values at heel of the dam for both models without and with SSI. It is abvious that soil-structure interaction phenomenon increases the stresses at heel of the dam.

Table2 : Maximum stress values at heel of the dam for models without and with SSI

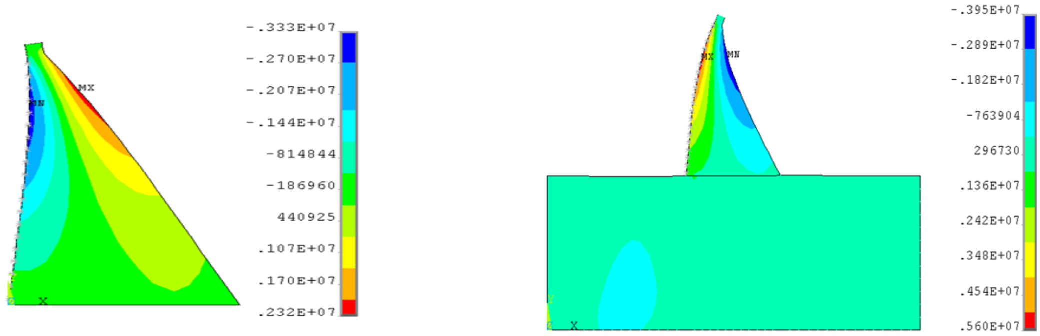
Stress	Model without SSI	Model with SSI
Horizontal stress (Mpa)	0.55	2.49
Vertical stress (Mpa)	2.47	3.03
Shear stress (Mpa)	0.69	1.55

Figs. 12, 13 and 14 represent the maximum horizontal and vertical as well as shear stress contours of the dam for both models without and with SSI. It is observed that the maximum stresses occur at lower and upper parts of the dam. However, the maximum stresses obtained from model with SSI are higher than ones obtained from model without SSI.



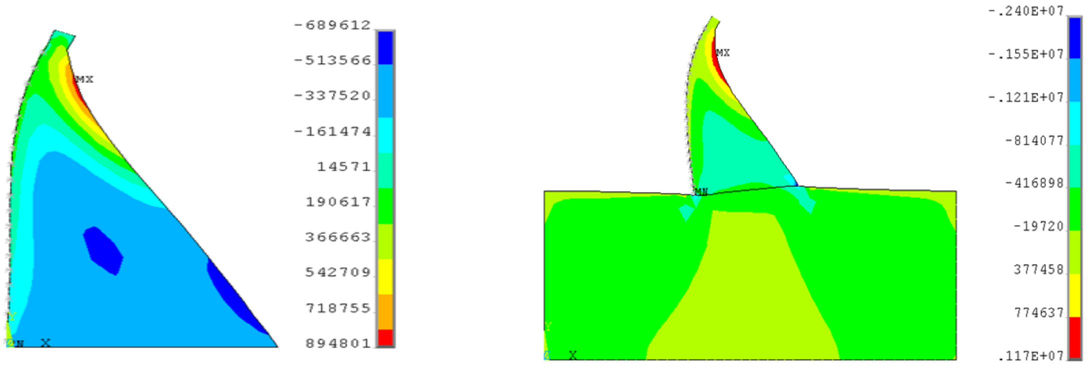
a) Model without SSI b) Model with SSI

Fig.11 Maximum horizontal stress contours of the dam [N/m^2]



a) Model without SSI b) Model with SSI

Fig.12 Maximum vertical stress contours of the dam [N/m^2]



a) Model without SSI b) Model with SSI

Fig.13 Maximum shear stress contours of the dam [N/m^2]

5. CONCLUSIONS

This paper presents the nonlinear seismic analysis of concrete gravity dams including the effect of soil-structure interaction phenomenon. For this purpose, two finite element models: model without SSI and model with SSI are taken into account to carry out the seismic response of Oued Fodda concrete dam.

From the numerical results obtained in the study, the following conclusions can be drawn:

- The numerical results show that the displacements and stresses increase in the dam body for model with SSI compared to model without SSI.
- Seismic analysis presents high stresses at the heel as well as the top of the dam for both models without and with SSI.
- It is also observed in model with SSI that the upper and lower parts of the dam are the most stressed zones, which causes concrete cracks in these regions.
- When the soil-structure interaction phenomenon is taken into account in the analysis, the shear force increases in the base, which can lead to instability of the dam.
- The seismic response of a concrete dam considering soil-structure interaction effect depends upon characteristics of the seismic motion, the foundation soil and the dam itself.

It is obvious that taking into account of soil-structure interaction phenomenon in the seismic analysis of concrete gravity dams affects greatly the response parameters. Hence, it is becomes imperative to carry out the soil-structure interaction analysis for massive structures such as concrete gravity dams.

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